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14. ABSTRACT
We designed and fabricated four mini-autonomous underwater vehicles (mAUVs). These vehicles are used to provide an inexpensive method for testing communication and control algorithms for multiple vehicles. The vehicle testing is being performed at the NSWCCD Acoustic Research Detachment, ARD, in Bayview, Idaho. The mechanical design of these vehicles was based on the Virginia Polytechnic Institute but with the addition of a Woods Hole Oceanographic Institute (WHOI) micro-modem that allowed for underwater communication and positioning. The control system for the mAUV also uses an innovative distributed computing approach developed at the UI consisting of multiple low-cost microcontrollers and was also different from the Virginia Polytechnic vehicle design. In addition, equipment for a Baseline Navigation System was included in this development to monitor and provide LBL positioning data for the mAUVs. This work supplements work currently underway at the University of Idaho funded by the Office of Naval Research.

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Fabrication of a Fleet of Mini-Autonomous Underwater Vehicles

FINAL TECHNICAL REPORT

May 26, 2006

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Abstract

In this work, we designed and fabricated four mini-autonomous underwater vehicles (mAUVs). These vehicles are used to provide an inexpensive method for testing communication and control algorithms for multiple vehicles. The vehicle testing is being performed at the NSWCCD Acoustic Research Detachment, ARD, in Bayview, Idaho. The mechanical design of these vehicles was based on the Virginia Polytechnic Institute and State University design of a similar vehicle by Dr. Daniel J. Stilwell but with the addition of a Woods Hole Oceanographic Institute (WHOI) micro-modem that allowed for underwater communication and positioning. Because of this addition, our vehicle was made larger than the Virginia Polytechnic vehicle and had a diameter of four inches and a length of forty inches. The control system for the mAUV also uses an innovative distributed computing approach developed at the UI consisting of multiple low-cost microcontrollers and was also different from the Virginia Polytechnic vehicle design. In addition, equipment for a Baseline Navigation System was included in this development to monitor and provide LBL positioning data for the mAUVs. This work supplements work currently underway at the University of Idaho funded by the Office of Naval Research.

LONG-TERM GOALS

The main long-term goal of this project is to build multiple autonomous underwater vehicles (AUVs) to allow verification of autonomous cooperative behavior. It is the intention to construct these vehicles using some of the technology developed by Dr Dan Stilwell of Virginia Tech University.

OBJECTIVES

A number of short-term objectives have been identified to support the long-term goal stated above. They include:

- Design an AUV that can accommodate a Woods Hole Oceanographic Institute (WHOI) micro-modem
- Equip the first vehicle with this acoustics communications equipment
- Test the prototype design, characterize the AUV's performance, and make appropriate modifications where necessary
- Implement the design improvements and construct three additional AUVs

APPROACH

The plan was to use as much of the electrical and mechanical engineering designs that were developed by Dr. Stilwell for their AUV in our vehicle. The mechanical parts were machined in the Department of Mechanical Engineering machine shop at the University of Idaho (UI). Fabrication was a cooperative effort by the UI Mechanical and Electrical and Computer Engineering Departments. After the construction, the initial vehicle was field tested at the NSWCCD ARD in Lake Pend Oreille, Idaho. This range allows underwater tracking as the vehicle performs maneuvers to test control algorithms. From the results of these tests, the next units were built and tested at the NSWCCD ARD facility. These vehicles were first tested in a solo mode to characterize the vehicle. After a model was used to verify the redesigned AUV, the systems were programmed for cooperative operation. Again these tests were conducted at the NSWCCD ARD in Lake Pend Oreille.

WORK COMPLETED

Dr. Stilwell has provided access to the engineering plans for his AUV design. A site visit by three UI engineers to Dr. Stilwell at his Virginia Tech facilities in Blacksburg, VA on October 12th, 2004 provided the basis for the technology transfer. A team of mechanical, electrical, and computer engineers has evaluated the design, modified the mechanical components and redesigned the electronics to equip the AUV with acoustics communications and navigation equipment. The first AUV was completed and field tested. Figure 1 shows the assembled, University of Idaho AUV. All four vehicles are shown in Figure 2.

<u>Design Modifications</u>

The main hardware for the mini-AUV is a modified version of the Virginia Tech mini-AUV. The hull diameter was increased to four inches and the overall length is now 40 inches for a 10:1 length to width ratio. The primary reason for the size increase was to accommodate the WHOI modem, and leave room for the two hydrophone sensor and associated computer hardware. The GPS mount was modified to attach to the main hull with the wiring coming in through a 10 pin waterproof connector on the bottom. A transducer for the WHOI micro-modem was added to the nose cone. The nose cone can

be rotated so the transducer can be placed either on top or the bottom of the AUV. The propulsion and fin control hardware are the same as the Virginia Tech mini-AUV.

The battery pack size was increased to provide power for the WHOI modem; it consists of 14 cells of 2000 milliamp-hour lithium polymer batteries, commonly used in radio-controlled aircraft. The batteries have a high energy density and are environmentally friendly in the event an AUV is lost. The battery cells are configured in two parallel banks of seven cells in series. Peak voltage is 29 volts and the pack is empty when it reaches 21 volts. The nominal main bus voltage is 25 volts with 4 amp hours of power available. The battery pack should provide 4 hours of operation at a submerged speed of 1 m/s, which yields a range in excess of 14 km.

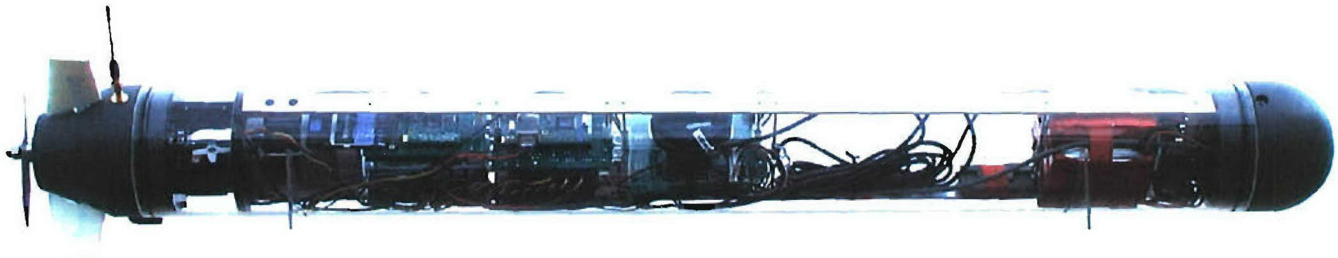

Figure 1. UI's Autonomous Underwater Vehicle, AUV

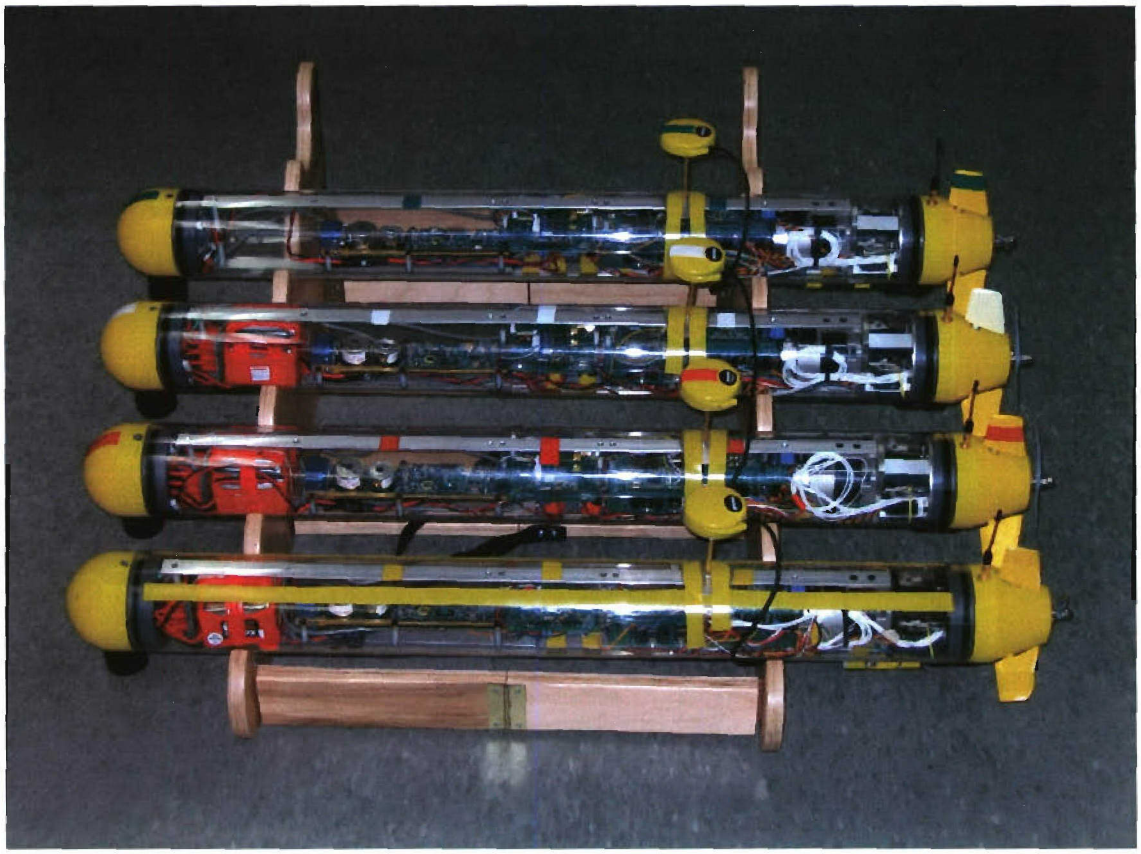

Figure 2. UI's Four Autonomous Underwater Vehicles

Design Features

The control system for the AUV was developed at the UI and uses a distributed approach consisting of multiple low-cost microcontrollers. The computational effort is divided between the various processors based on functional tasks. The advantages are in the areas of scalability, reliability, and rapid development. Using a distributed approach, the system design has a high degree of modularity allowing parallel independent development. A diagram of the processing architecture is illustrated in Figure 3. Four nodes communicate over a 10Mbps Ethernet based network using conventional Ethernet protocols. The functions that the four processors provide are sensor input, off-vehicle communications, control command and data logging, and propulsion control. A fifth processor operates in a master-slave configuration to serve a WEB page for high-speed data transfers between the AUV and a PC at dockside or on a tender craft. The AUV also communicates with the PC operator using a long-range, low data rate communications channel for controlling the AUV in remote operations mode (ROV) while the AUV is on the surface. While under the surface, the communications processor uses a WHOI micro-modem for determining its position and communicating with other AUV's or surface craft that is equipped for acoustic communications.

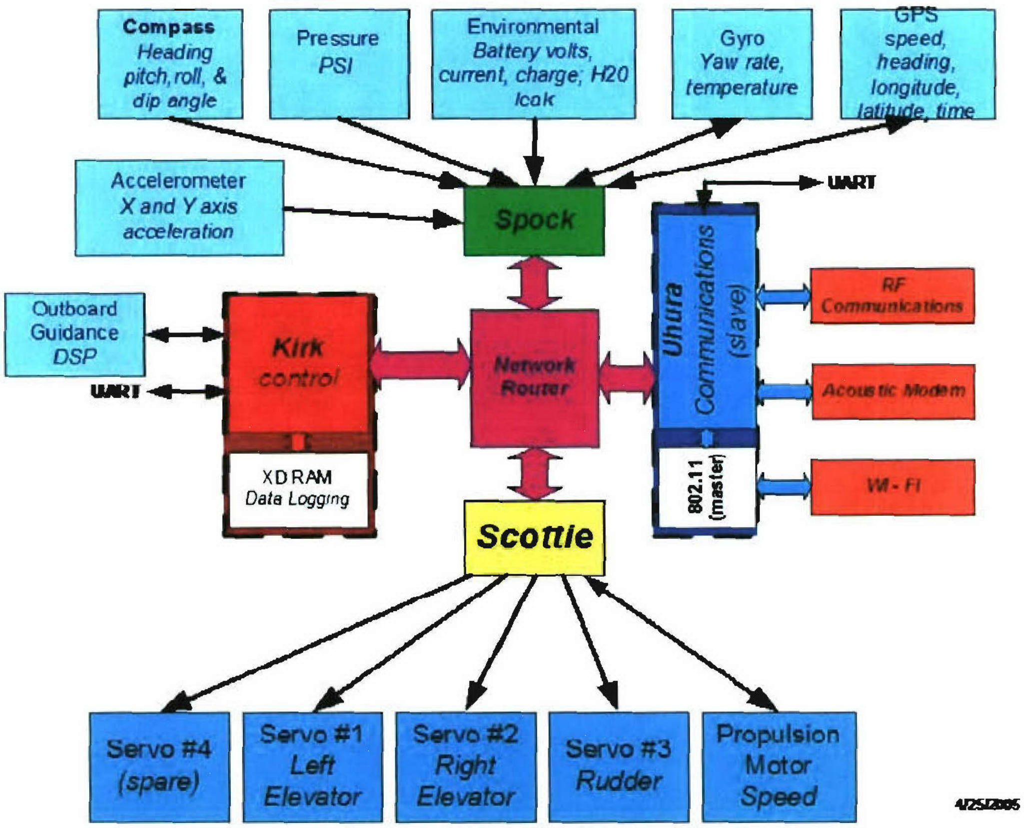

Figure 3. UI's Control System for the mini-Autonomous Underwater Vehicle

The AUV has a number of sensors and systems for autonomous control and navigation as discussed below:

Communication System:
The AUV has a radio modem for remote control and telemetry at long range while on the surface. It also has a wi-fi card for broadband data upload and download. The AUV actually hosts its own web page where trim values and sensor zero points can be set and mission logs can be downloaded. We are able to upload different missions and controllers on the web page. In addition, the WHOI modem provides underwater communications capabilities. The WHOI modem communication was successfully tested in October, 2005. All the communication systems are now in operation and have been extensively field tested.

Sensors:
The AUV has a number of sensors on board. The primary sensors currently measure depth, heading, and pitch and are used to control the sub. In addition, other sensors currently measure roll, yaw rate, internal temperature, internal water detection, and battery voltage. Hull space and electronic connections are available for the two hydrophone sensor that is currently under development.

Navigation System:
GPS is used for position sensing while the vehicle is on the surface and the WHOI modem provide position data both on the surface and while submerged. The WHOI modem sends a navigation ping which is echoed back by three Hydroid transponders. The WHOI modem then provides time of flight for each transponder. Given the location of the transponders, and the speed of sound in water, it is possible to calculate a position. The WHOI modem has been successfully field tested in all four vehicles.

Control System:
The AUV's computer system has independent control on all three fins as well as control with feedback on propeller rpm both forward and reverse. Currently the maximum rpm ever used on the AUV is 4000 rpm. Most missions use 1000 rpm which produces an underwater velocity of 1.0 m/s and a surface velocity of 0.8 m/s. The current control scheme uses fin trim to offset the effects of engine torque. The AUV is trimmed so it maintains heading and depth with zero control input while underwater. The lower fins are coupled through software with the rudder to offset rolling while turning.

Other Features:
The AUV has a salmon pinger attached that provides a traceable acoustic ping that is independent of the AUV systems. The pinger should allow for the recovery of the AUV should it become lost or suffer a power failure, become entangled, or encounter some other mishap. The design of the AUV also includes many safety features to abort missions should operating parameters exceed predefined levels.

- Mission run time. A timer during the mission will trigger an abort after 18 minutes.
- Main Bus Voltage. If the main bus voltage falls below 21 volts (depleted batteries).
- Pitch and Roll limit. A pitch or roll of 45 degrees will abort the mission.
- Water Detector. Water on board causes a mission abort.

- Waypoint distance. If the navigation system determines the AUV is over 100 meters from the next waypoint, the mission is aborted. This will prevent an error in the waypoint list (typo or wrong latitude or longitude) from navigating the AUV too far off track.

Another useful feature we have incorporated is the return to base mission. A GPS waypoint is set close to the base station such that the AUV can always head toward that point from anywhere in the expected operating area. Operation of the AUV during the field test is extremely simple once all the equipment is setup. Each mission is started with a click of the mouse on the base station PC. Once the mission is completed, the return to base mission is run to bring the AUV back and reposition itself for the next mission.

RESULTS

The first AUV has been fabricated and has undergone a number of field tests. Initial testing was carried out on the bench to check electronic and mechanical systems. Tests were then carried out in a float tank in the Civil Engineering building at the UI to test water tight seal integrity and buoyancy. The next series of field tests were conducted in the pool at the UI Swim center. These tests checked for trim and controllability of the AUV under both manual control, via radio modem from the base station, and while being controlled by its onboard computer systems both on the surface and when submerged. The next phase of field testing was conducted at the Clay Pit Reservoir located near Bovill, Idaho. The ability of the AUV to navigate on the surface using GPS and waypoint navigation was tested.

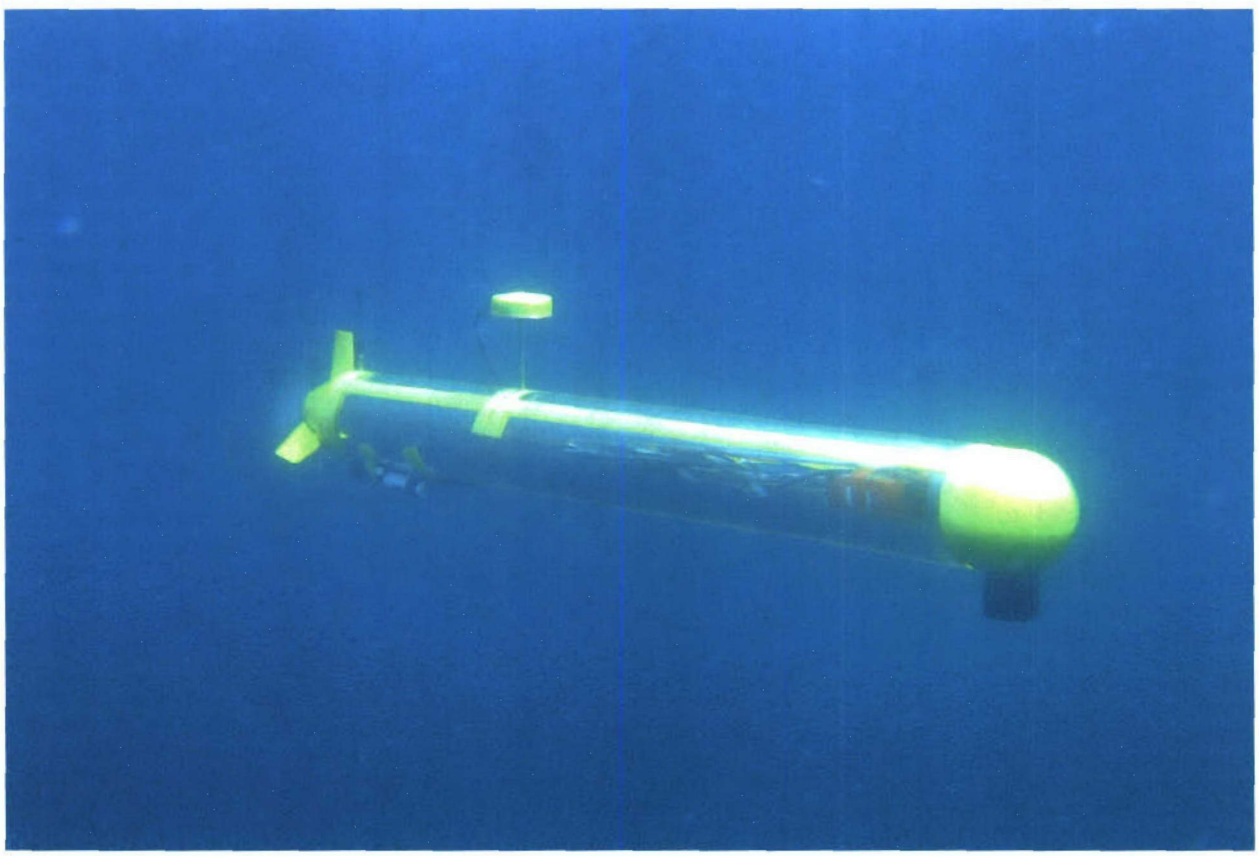

Figure 4. UI's AUV in Buttonhook Bay, Lake Pend Oreille, Idaho

Most of our field tests have been done at the NSWCCD ARD in Lake Pend Oreille, Idaho. In this testing, the WHOI modem was used to ping the Hydroid transponders for position information needed for navigation. Figure 4 shows the vehicle during some of these tests at Buttonhook Bay of Lake Pend Oreille. In the figure the GPS antennae is clearly shown as the tower located on top of the vehicle and the transducer used with the WHOI micro-modem for communication and navigation is shown on the nose cone underneath the vehicle. A number of multi-vehicle formation tests have been done. Figure 5 shows the results of one of these tests. In this test, the vehicles were using a leader-follower control algorithm where the leader broadcasts its position via the WHOI modem and the followers use this information to maintain the formation.

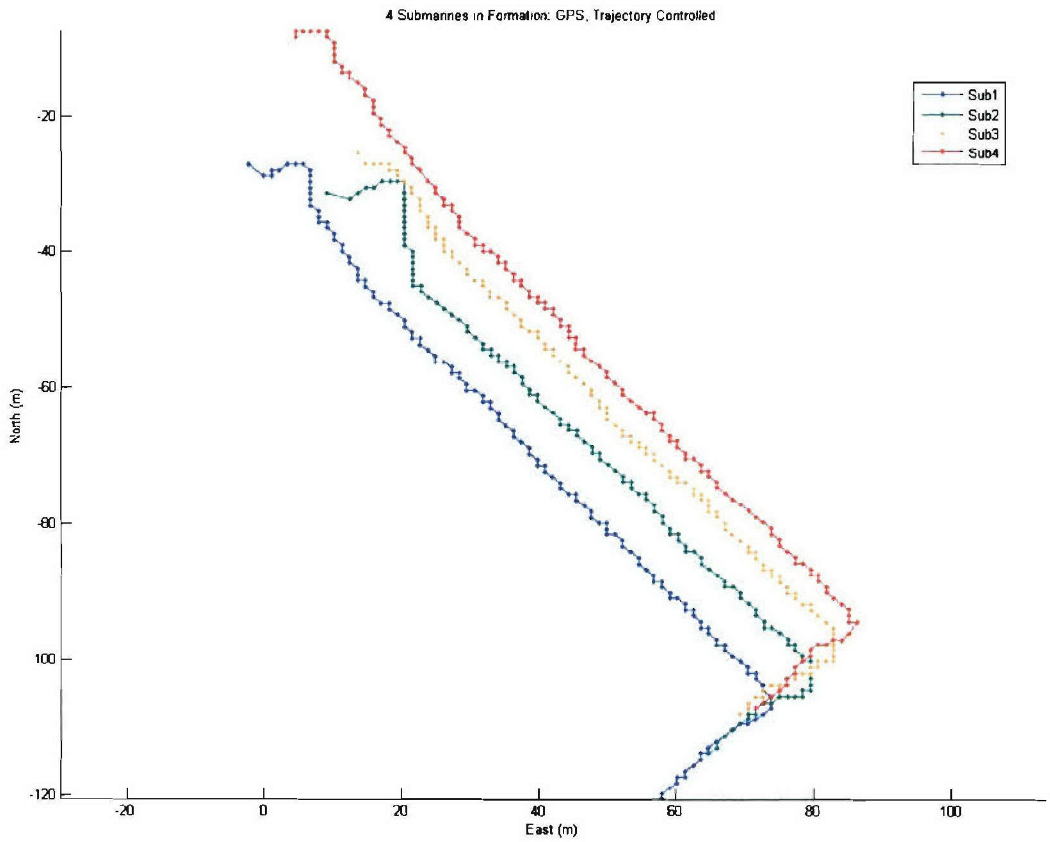

Figure 5. Formation Trajectories of UI's Four AUVs

IMPACT/APPLICATIONS

The results of this project are expected to have a direct impact on the ability of the Navy to conduct ocean searches. In particular, the use of multiple autonomous vehicles should significantly reduce the time required to conduct searches for mines in littoral regions. The fabrication of these vehicles will

allow field testing of the control and communication algorithms being developed for cooperative behavior between vehicles so that they will be able to more effectively and aggressively search for mines.

RELATED PROJECTS

This work is related to a number of previous funded ONR projects: Decentralized Control of Multiple Autonomous Underwater Vehicles (ONR Grant Number: N000140310634), Decentralized Control of Multiple Autonomous Crawlers and Swimmers (ONR Grant Number: N000140310848), and Communication and Control for Fleets of Autonomous Underwater Vehicles (N000140410506).

REFERENCES

Wick, C. E., Stilwell, D. J., "USNA-1: A Miniature, Low-Cost, Autonomous Underwater Vehicle," Sea Technology, Vol. 43, No. 6, pp. 17-25, 2002 (invited).

Gadre, A. S., Mach, J. J., Stilwell, D. J., Wick, C. E., "Design of a Prototype Miniature Autonomous Underwater Vehicle," Proceedings of the IEEE/RSJ Intelligent Robotics and Systems, Las Vegas, NV, 2003 (to be published).

Stilwell, D. J., Bishop, B. E., "Decentralized Control and Path Planning for Platoons of Autonomous Vehicles," Proceedings of the IEEE International Conference on Decision and Control, Las Vegas, NV, pp. 10-13, 2002 (invited).

Stilwell, D. J., "Decentralized Control Synthesis for a Platoon of Autonomous Vehicles," Proceedings of the IEEE International Conference on Robotics and Automation, Washington, D. C., pp. 744—749, 2002.

Bishop, B. E., Stilwell, D. J., "On the Application of Redundant Manipulator Techniques to the Control of a Platoon of Autonomous Vehicles," Proceedings of the IEEE Conference on Control Applications, Mexico City, Mexico, pp. 823-828, 2001.

Stilwell, D. J., Wick, C. E., Bishop, B. E., "Small Inertial Sensors for a Miniature Autonomous Underwater Vehicle," Proceedings of the IEEE Conference on Control Applications, Mexico City, Mexico, pp. 841-846, 2001.

Wick, C. E., Stilwell, D. J., "Design, Guidance, and Control of a Miniature Autonomous Underwater Vehicle," Proceedings of IEEE/MTS Oceans, Honolulu, HI, pp. 423 -428, 2001

Stilwell, D. J., Campbell, D. J., "Experiments in Calibration and Alignment of Inertial Sensors for UUV Applications," Proceedings of the of the Unmanned Untethered Submersible Technology Symposium, Durham, NH, 2001.

Stilwell, D. J., Bishop, B. E., "A Strategy for Controlling Autonomous Robot Platoons," Proceedings of the IEEE Conference on Decision and Control, pp. 3483-3488, Sydney, Australia, 2000.